TIME DOMAIN ELECTROMAGNETIC SURVEY FOR ASSISTING IN DETERMINING THE GROUNDWATER RESOURCES ON PROPERTY LOCATED IN THE SOUTH KONA DISTRICT BELOW KEALAKEKUA, HAWAII

Project Number R5-0129

October 2014

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TABLE OF CONTENTS

LIST OF FIGURES AT THE END OF THE TEXT

LIST OF TABLES

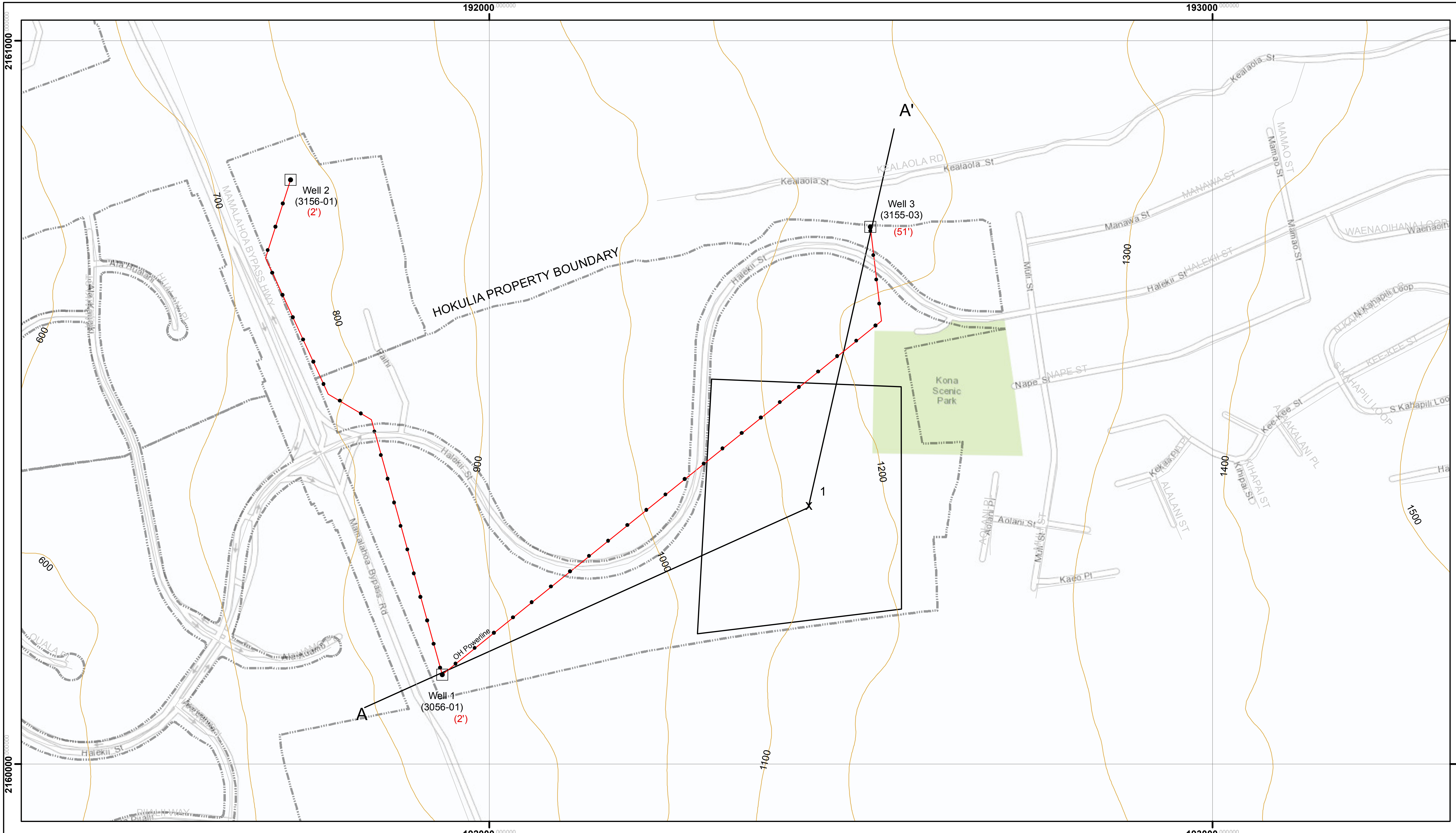
APPENDICES

1.0 INTRODUCTION

This report contains the procedures and results of a surface Time Domain Electromagnetic (TDEM) geophysical survey performed for groundwater resource evaluation on property located in the South Kona District west of the town of Kealakekua, Hawaii. The project site included property located between the Mamalahoa Bypass Road and the Clarence Lum Won Park. Zapata Incorporated (ZAPATA) performed the survey for 1250 Oceanside, LLC (OSLLC) and Tom Nance Water Resource Engineering (TNWRE) on October 14 and 15, 2014.

The main objective of the TDEM survey was to determine if basal or high-level groundwater underlies a proposed well site on the property. The survey was conducted at one TDEM sounding site to help determine the location for a future groundwater well. The project boundary and location of the TDEM sounding taken during this survey are shown on Figure 1-1.

TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) of the subsurface. From the geoelectric section, information about geology and water quality can be inferred. This is possible because the electrical resistivity of the earth depends on lithology, porosity, degree of saturation, and concentration of dissolved solids in the groundwater. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for water well placement and well completion depths.



N

0 200 400 800 1,200 Feet

EXPLANATION

- Well Location (Head in feet)
- TDEM Sounding
- OH Power Line
- A—A' Section Line

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Geophysical TDEM Survey
Location Map
South Kona District
Island of Hawaii

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R50129	October, 2014	JMN	RJB	1:4800	1-1

2.0 GEOLOGY/HYDROGEOLOGY

Groundwater resources occur on the Hawaiian Islands basically in two modes:

- In a basal mode where a lens of fresh water floats on seawater, and
- In a high-level mode where the fresh groundwater occurrence is controlled by damming or confining structures (i.e. dikes, intrusives, impermeable layers, etc).

Figure 2-1 illustrates the basic geologic and hydrologic framework of the Island of Hawaii and the two modes of groundwater occurrences. Fresh groundwater may also occur in areas between these two modes, but production is expected to be variable. TDEM soundings previously taken on Hawaii have reliably mapped basal mode groundwater and the boundary between fresh water in the basal mode and high-level water occurrences.

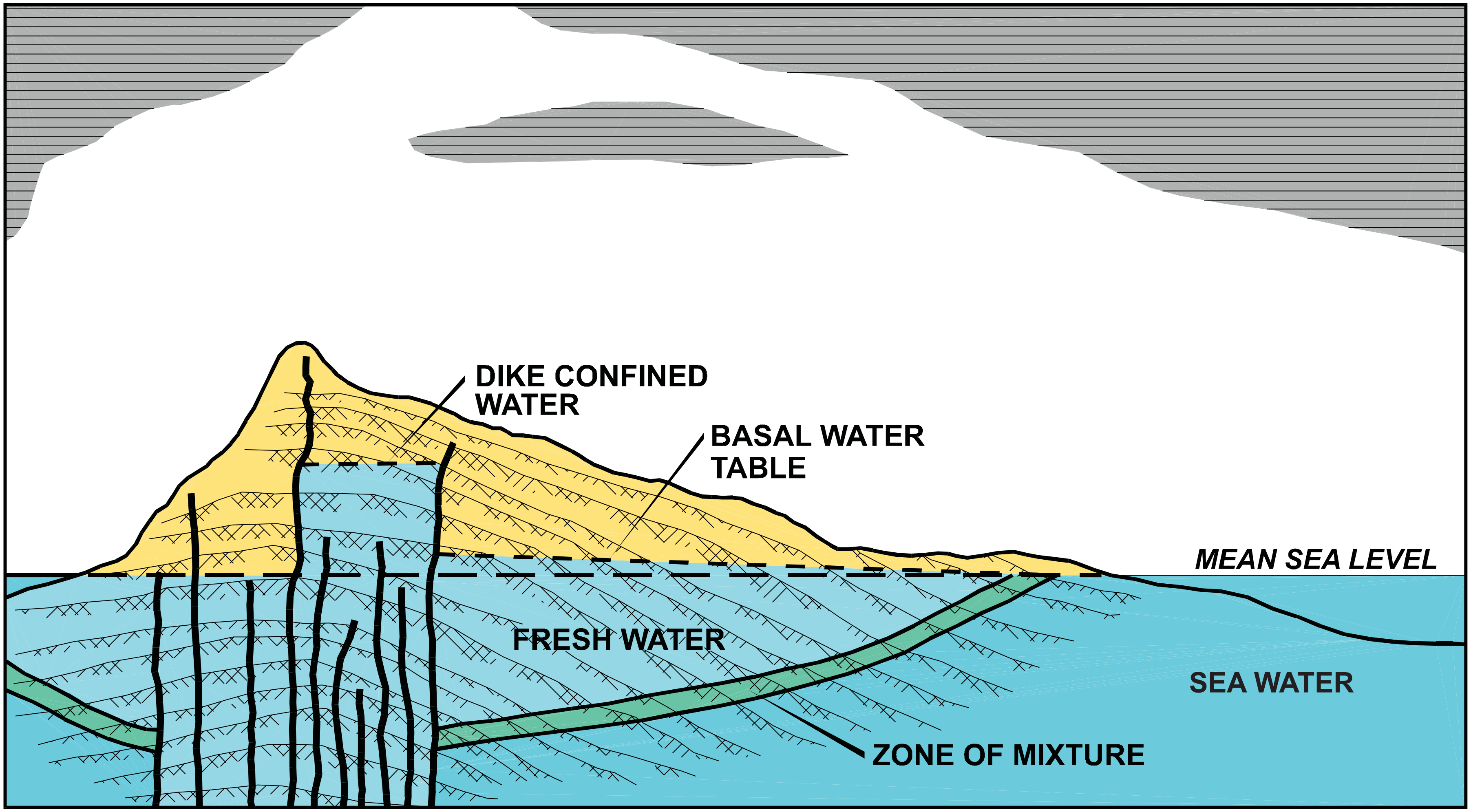
Basal mode groundwater is shown to rest approximately at sea level near the ocean surrounding the Island of Hawaii (reference Figure 2-1). This is due to the fact that the volcanic rocks, which comprise the island, allow rainfall to percolate with little impedance directly downward through the rock mass and the fresh water floats directly on seawater encroaching from the ocean. Fresh water flows laterally toward the ocean causing the fresh groundwater lens to be thinner near the shoreline. When groundwater is under static equilibrium conditions, the Ghyben-Herzberg Principle states that for every one foot of fresh water above sea level approximately 40 feet of fresh water will exist below sea level as shown in Figure 2-2. The change from fresh water to seawater (transition zone) at depth may be relatively sharp (i.e. occurring over several tens of feet) or more gradual, depending upon hydrologic flux, horizontal and vertical permeability contrast, and other geologic factors. It is assumed when resolving TDEM sounding data, that seawater saturated volcanics occur at the midpoint of the transition zone.

TDEM surveys are utilized to map the resistivity stratification of the subsurface. From numerous TDEM surveys on Hawaii and calibration of TDEM data at groundwater wells, characteristic ranges of subsurface resistivities have been derived for the geologic/hydrologic units shown in Figure 2-3. Some overlap in resistivity values occurs between the units; however, other factors, such as ground elevation, can be used to help separate the units. Therefore, the main geologic/hydrologic units that can be derived from TDEM surveys include:

- Depth to seawater-saturated volcanic rocks. This occurs in basal mode situations, and by using the Ghyben-Herzberg principle the thickness of the basal fresh water lens can be calculated.
- Weathered volcanic layers (laterite). These low to intermediate resistivity units are generally relatively thin layers (10 to 100 feet thick) that normally occur at or near the ground surface.
- Clay-poor and fresh water saturated volcanic rocks. These formations generally exhibit high resistivity values (>500 ohm-m). The extent of fresh water saturation is normally

based on geographic and elevation information, and it should be noted that fresh water layers cannot be directly detected in the TDEM data.

Groundwater damming structures (i.e. intrusives, dikes, etc.) are inferred with TDEM data by uncharacteristic sounding curves (distorted by 2-dimensional [2-D] structures), and by soundings that change between detection of seawater at depth (indicating basal mode groundwater) and soundings that map high resistivities to depths below sea level (indicating high-level groundwater).



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Schematic Hydrogeologic Cross Section Island of Hawaii

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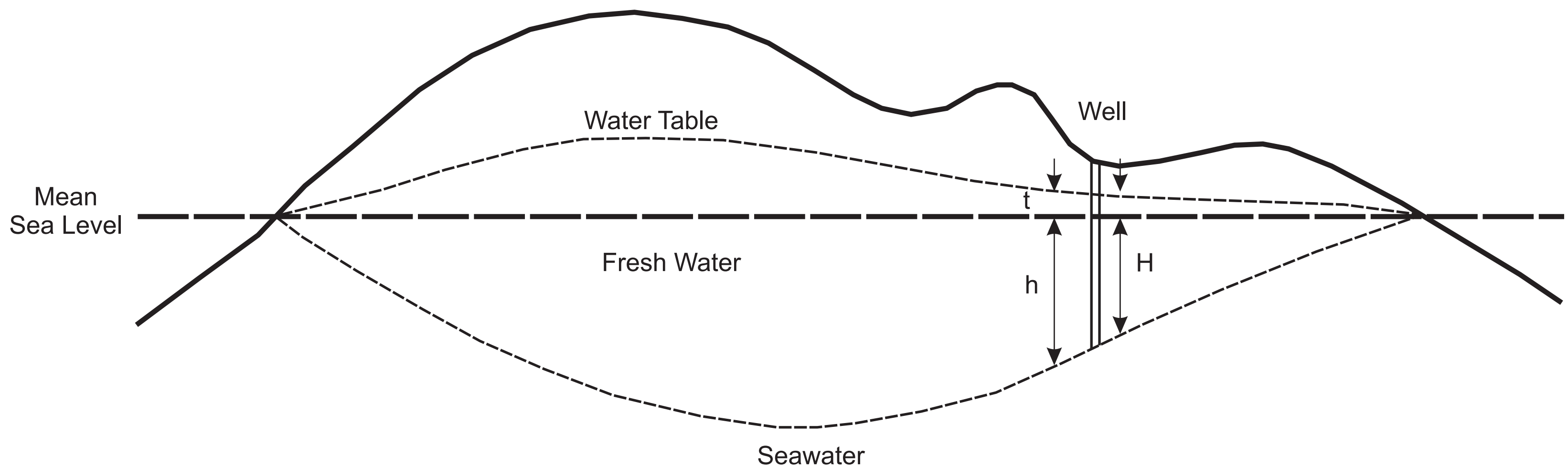

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From: Herzberg

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Illustration of the Ghyben-Herzberg Principle

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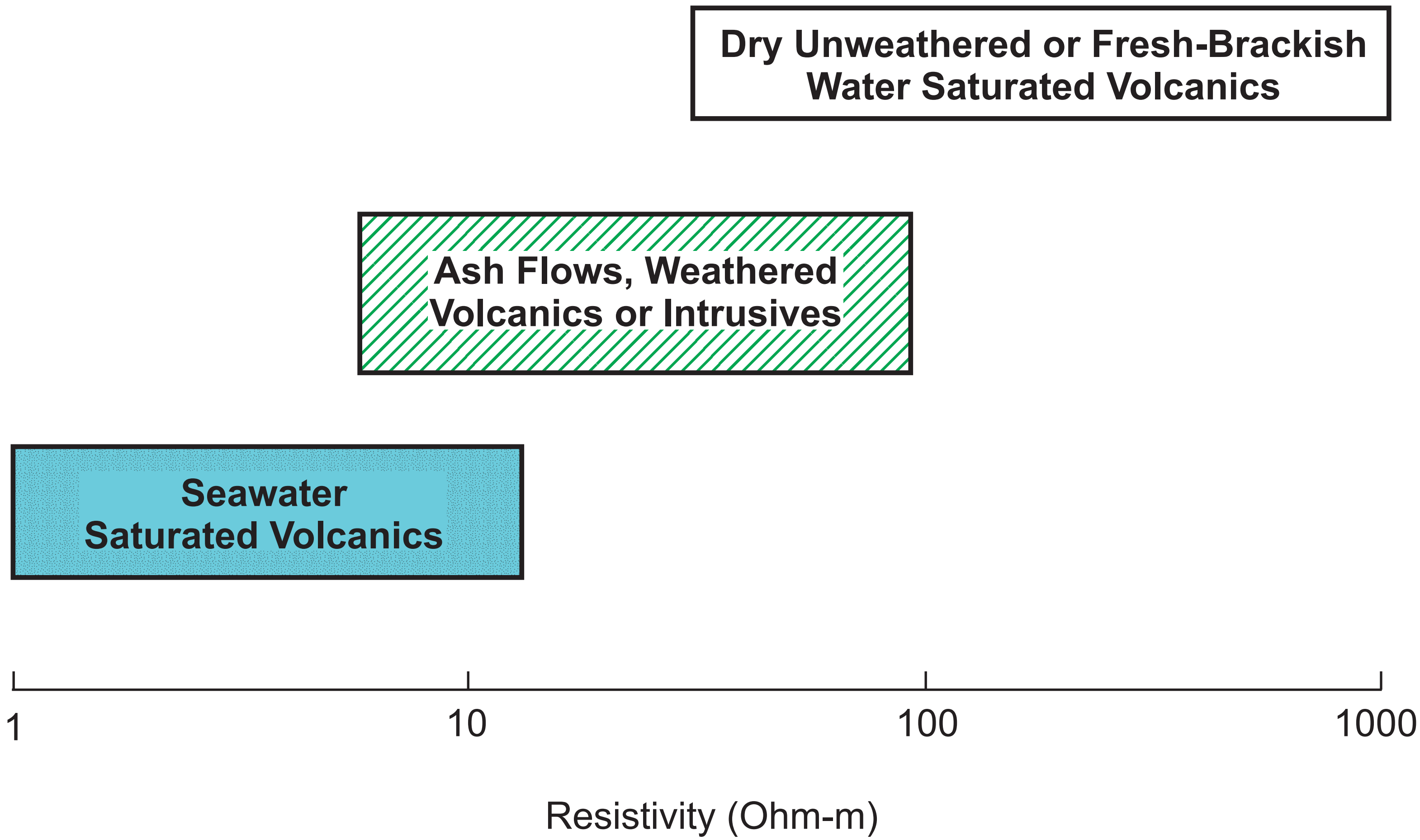

ZAPATA TRUST • INTEGRITY • QUALITY	Hokulia Project **1250 Oceanside, LLC** *Roseville, California*	**Characteristic Resistivity Ranges** *Property Below Kealakekua* *Island of Hawaii*

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3.0 DATA ACQUISITION AND LOGISTICS

ZAPATA mobilized a field crew consisting of a project geophysicist and geophysical technician to perform the geophysical surveys. The field crew and TDEM equipment were mobilized from Golden, Colorado to Kailua-Kona, Hawaii. Prior to conducting the surveys, ZAPATA personnel coordinated with OSLLC and TNWRE personnel to determine property access and logistics. During the field work the project geophysicist coordinated with TNWRE daily to relay preliminary data results and determine project direction. A daily log of field activities during the TDEM surveys is given in Table 3-1.

The Geonics EM37 geophysical system was used for the TDEM surveys. The EM37 system includes both a portable motor-generator powered transmitter and a PROTEM digital receiver. The main purpose of the TDEM measurements is to derive both the vertical and lateral variations in the geoelectric section (resistivity) of the subsurface. To accomplish this, a single TDEM sounding was collected using a central-loop array. A transmitter wire-loop with rectangular dimensions was constructed using 12-gauge insulated copper wire laid on the ground surface (illustrated in Figure 3-1). Due to several factors during the survey (location of access roads and a rock wall along the southern property boundary), the dimension of the transmitter wire-loop used was determined to be 1,000 feet by 1,000 feet. The EM37 transmitter was placed in the NE corner of the transmitter loop and square-wave current pulses were driven through the wire-loop using a current of 14 amperes. The current pulses induce eddy current flow in the subsurface of the ground. A solid-core receiver coil (1-meter diameter) attached to the PROTEM receiver was positioned near the center of the wire-loop and was used to record the decay of the secondary magnetic field from the eddy currents induced in the subsurface. The effective exploration depth of the 1,000-ft by 1,000-ft transmitter wire-loop array has been determined to be approximately 2,000 feet below the ground surface. Therefore, at surface elevation of 1,000 feet, a search depth of approximately 1,000 feet below sea level is obtained. Greater exploration depths are reached with larger transmitter wire-loops and there are several factors that affect the depth of investigation; these include ground resistivity (in ohm-m) and surrounding ambient cultural interference (i.e. 60-cycle powerline, metal pipeline, etc). The principles of TDEM with case histories are given in a technical note in Appendix A.

The TDEM data collected at the sounding site consisted of measurements utilizing several receiver gain settings and two transmitter frequencies in order to obtain data over the longest time interval possible. The data were recorded using base frequencies of 3 and 30 Hz to obtain the maximum search depth for the TDEM sounding. For data quality control (QC) purposes, additional measurements were collected at two offset locations (100 feet north and south directions from the center), for comparison to the central-loop data. The data from the sounding was recorded in solid-state memory in the PROTEM receiver and transferred to a personal computer (PC) for processing. The TDEM data collected at the site was of excellent quality. This was mainly due to Well #1 pump being shut down during data acquisition. The QC offset data for this sounding were also determined to be of good quality, and were therefore not adversely affected by local cultural interference from an overhead powerline located at the site.

The northwest (NW) corner of the transmitter wire-loop was located along Halekii Street while the NE corner was located in the parking lot west of Clarence Lum Won Park (Figure 1-1). The SW and SE corners were situated near a rock wall which was located along the southern boundary of the property. In each case, landmarks (such as road, gate, rock wall, etc.) were used to position the transmitter wire-loop on the map along with using a measuring device (hip-chain) and compass to locate the loop corners and the center. In addition, a hand-held WAAS-enabled global positioning system (GPS) with horizontal accuracy of 15 feet was used to measure the transmitter corners and center of the sounding. The GPS coordinates were utilized to position the loop center on a geo-referenced topographic map and the loop center elevation was subsequently derived from that position. One TDEM sounding was measured during 1.5 days of fieldwork. The GPS coordinates and elevations of the TDEM transmitter wire-loop corners, center, wells and main road junctions are shown in Table 3-2 in Appendix B. Surface elevations of the water wells (1, 2 and 3) were supplied by the client and posted on the map.

Table 3-1
Daily Log of Field Activities for TDEM Survey
1250 Oceanside LLC, South Kona District, Kealakekua, Hawaii

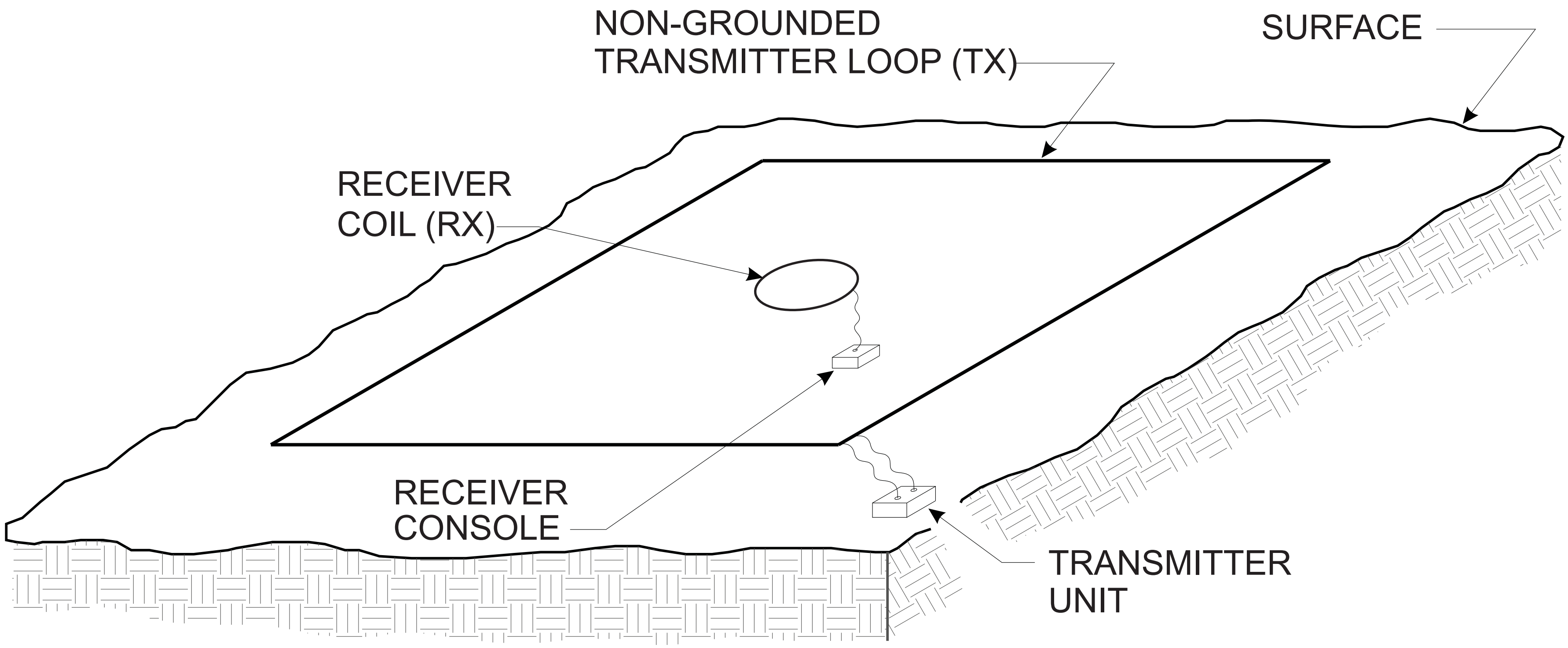
Date (2014)	Activity
October 6	Mobilize TDEM equipment from Golden, CO to Kailua-Kona, HI.
October 13	Mobilize ZAPATA personnel from Golden, CO to Kailua-Kona, HI.
October 14	Pick up TDEM equipment from FedEx and organize into field vehicles. Meet with 1250 OSLLC personnel at onsite office trailer. Discuss survey and recon TDEM loop location. Lay out transmitter wire-loop and collect data on Sounding Hoku-1. Download data and perform preliminary analysis.
October 15	Discuss results with 1250 OSLLC and TNWRE in AM. Reacquire TDEM data on Sounding Hoku-1. Pick up wire-loop, collect GPS data and pack up TDEM equipment. Download data and perform preliminary analysis. Discuss results with TNWRE in PM.
October 16	Demobilize TDEM equipment and ZAPATA personnel from Kailua-Kona, HI to Golden, CO.

Table 3-2

GPS Coordinates of TDEM Sounding, NAD 83 Latitude/Longitude (Decimal Degrees)

1250 Oceanside LLC, South Kona District, Kealakekua, Hawaii

ID	Latitude	Longitude	Elev (feet)	Comments
Loop 1 NW Corner	19.51579579	-155.9316009	1100	Loop 1 NW Corner along Halekii Street
Loop 1 NE Corner	19.51574106	-155.9291037	1240	Loop 1 NE Corner in parking lot below Clearance Lum Won Park
Loop 1_Center	19.51436651	-155.9298206	1120	Loop 1 Center located approx 450 feet from east side of loop
Well 1 (State Well 3056-01)	19.51205285	-155.9350811	811	Ground elevation reported from client, TD = -38 feet below sea level
Well 2 (State Well 3156-01)	19.51819511	-155.937188	750	Ground elevation reported from client
Well 3 (State Well 3155-03)	19.51772925	-155.9295489	1154	Ground elevation reported from client, TD = -41 feet below sea level
Halekii St & Mama Bypass Rd	19.51485836	-155.9367192	780	Junction of Halekii Street and Mamalahoa Bypass Road
Halekii St & Muli Street	19.51676482	-155.9273886	1260	Junction of Halekii Street and Muli Street



ZAPATA TRUST · INTEGRITY · QUALITY	Hokulia Project **1250 Oceanside, LLC** *Roseville, California*	**Schematic layout of TDEM system with locations of TX and RX for Central Loop Array measurements**

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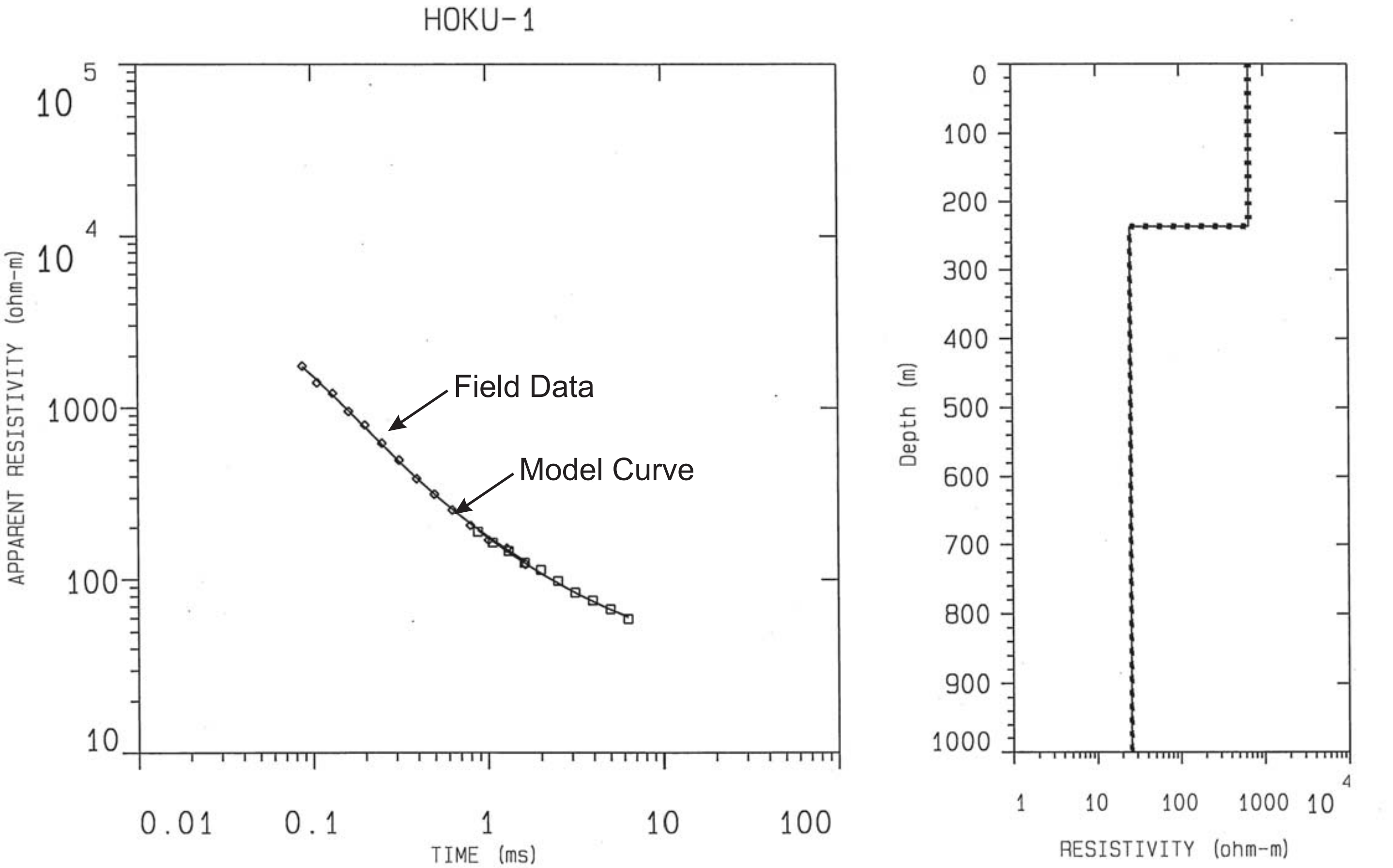
4.0 DATA PROCESSING

The geophysical field data collected for each TDEM sounding was transferred from the Geonics PROTEM ™ digital receiver to a PC for editing and processing. The processing of TDEM data begins with averaging of the electromotive forces recorded for positive and negative receiver polarities. Next, the measurements collected at two base frequencies (3 and 30 Hz) and several amplifier gains are combined to give one voltage decay curve (transient). The electromotive forces (EMFs) collected from 20 logarithmical spaced time-channels (gates) of the decay curve are subsequently entered into the TEMIXXL™ (Interpex Ltd.) inversion program. The data are then used to obtain a one-dimensional (1-D) geoelectric section that best matches the observed (field data) decay curve from the sounding.

The TEMIXXL inversion program requires an initial model of the geoelectric section measured. The initial model includes the number of layers, resistivities and thickness for each of the layers. This model is usually derived from knowledge of the geologic section or from data obtained from drillholes or electric logs. The inversion program is then allowed to adjust the layer thickness and the resistivities, so that the model curve converges to best fit the field data. The inversion program does not change the total number of layers within the model curve, but allows all other parameters to change freely or they can be fixed constant. To determine the influence of the number of layers on the solution, separate inversions with a different number of layers are modeled for the sounding data. Subsequently, the model with the least number of layers that best fits the field data is used. An example of the output of the inversion program is shown on Figure 4-1 for Sounding 1 (Hoku-1). The figure shows the measured data points (in terms of apparent resistivity) superimposed on a solid line on the left panel. The solid line represents the computed forward model for the geoelectric section on the right panel. The geoelectric section is the best match obtained by the inversion program. Figure 4-2 shows the tabulated inversion parameters consisting of measured data, computed data for best match solutions and an example of the table of inversion statistics. A two-layer inversion model is shown for the Sounding 1. The model displays an upper layer with high resistivity (667 ohm-m) overlying a second layer with intermediate resistivity (25 ohm-m). The depth to the top of the second layer is modeled at 344 feet above sea level (ASL) in the section. The second layer is interpreted as weathered or intrusive volcanic units to the maximum exploration depth of the sounding (approximately 1,000 feet BSL).

The interpreted geoelectric section derived from each TDEM sounding is not unique. The magnitude of each individual layer resistivity and thickness can normally be varied within a limited range with no significant change to the fit of the geoelectric model of the data. This variation is termed equivalence. An equivalence analysis was performed for the TDEM sounding. Both Figures 4-1 and 4-2 show the equivalence analysis for Sounding Hoku-1. This sounding is typical of TDEM data which shows a +/-5% equivalence in depth determinations and individual layer resistivities. The inversion results for the TDEM sounding are given in Appendix B.



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Sounding HOKU-1
Example Inversion Output
Apparent Resistivity Curve
Property Below Kealakekua
Island of Hawaii

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DATA SET: HOKU-1

CLIENT:	1250 Oceanside LLC	DATE:	10-14-2014
LOCATION:	Kealakeakua, Hawaii	SOUNDING:	1
COUNTY:	HAWAII	ELEVATION:	341.00 m
PROJECT:	Hokulia, Hawaii	EQUIPMENT:	Geonics PROTEM
LOOP SIZE:	305.000 m by 305.000 m	AZIMUTH:	
COIL LOC:	0.000 m (X), 0.000 m (Y)	TIME CONSTANT:	NONE
SOUNDING COORDINATES:	E: 1.0000 N: 200.0000	SLOPE:	NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.599 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			341.0	1120.0	
1	667.0	236.1	104.8	343.8	0.354
2	25.43				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	628.475	667.034	714.763
	2	24.434	25.438	26.503
THICK	1	233.147	236.143	239.265
DEPTH	1	233.147	236.143	239.265

Equivalence Analysis

CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 5 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.881	342.4	333.0	2.75
2	1.06	264.0	257.0	2.67
3	1.31	187.0	192.5	-2.93
4	1.61	140.3	141.3	-0.691

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
5	2.00	94.59	101.6	-7.45
6	2.50	67.57	71.02	-5.09
7	3.14	48.42	48.55	-0.268
8	3.95	31.87	32.50	-1.95
9	4.99	21.17	21.31	-0.654
10	6.31	14.29	13.72	3.97

CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 2 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
11	0.0881	3869.6	3918.7	-1.26
12	0.106	3320.1	3145.6	5.25
13	0.131	2460.7	2543.9	-3.38
14	0.161	2102.0	2076.6	1.20
15	0.200	1619.6	1693.7	-4.57
16	0.250	1337.6	1367.3	-2.21
17	0.314	1056.9	1088.8	-3.02
18	0.395	867.1	855.4	1.34
19	0.499	659.7	659.0	0.112
20	0.631	506.0	498.9	1.40
21	0.799	384.1	370.4	3.55
22	1.01	287.2	268.7	6.42
23	1.28	186.8	191.2	-2.36
24	1.63	140.7	132.6	5.77

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.89		
P 2	-0.03	0.96	
T 1	0.02	0.01	1.00

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Sounding HOKU-1
Example of Tabulated Data From Inversion
Property Below Kealakekua
Island of Hawaii

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R50129	October, 2014	JMN	RJB	No Scale	4-2

5.0 INTERPRETATION AND RESULTS

5.1 TDEM SOUNDING DATA

From each TDEM sounding, the geoelectric section of the subsurface is derived. The results of the one-dimensional (1-D) inversion from an individual TDEM sounding can be linked together as layers with similar resistivities, to create a 2-D geoelectric cross-section along a transect line. During this project one TDEM sounding was collected on the OSLLC property and from that sounding a geoelectric cross-section was generated. The correlation between the geoelectric layers and lithologic units (illustrated on Figure 2-3) was used to interpret the geoelectric cross-section.

5.2 GEOELECTRIC CROSS-SECTION – LINE 1 (A-A')

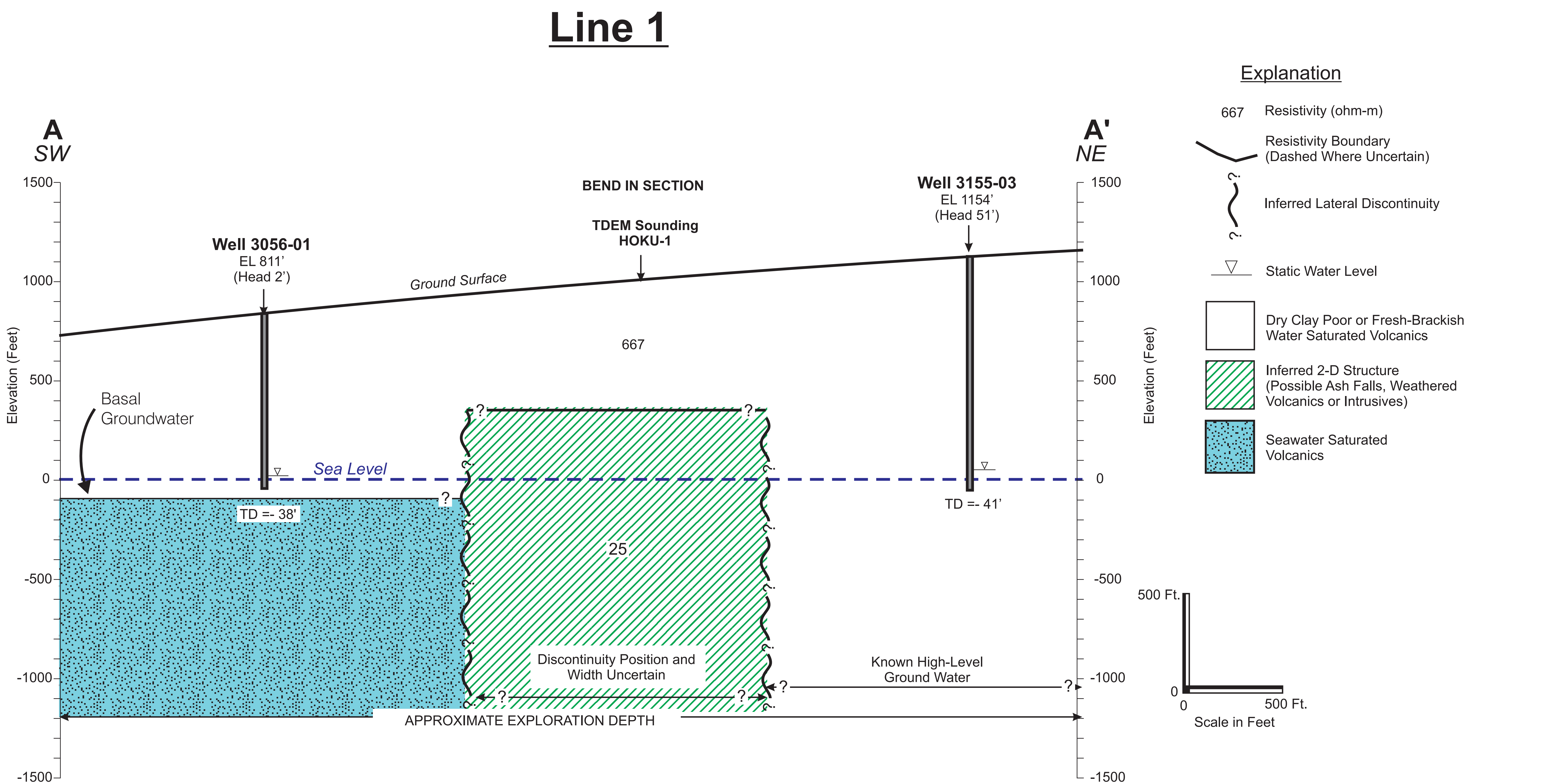
Figure 5-1 shows the layered geoelectric cross-section interpreted from the TDEM data collected at the project site. The center of Sounding Hoku-1 was located above and east of Halekii Street between Wells 1 and 3, which lends itself to generate a southwest to northeast profile. An overhead powerline was located between the two wells, which crossed the northwestern corner of the transmitter loop.

In the geoelectric cross-section a two-layer resistivity model is interpreted for Sounding Hoku-1. The upper layer exhibits high resistivity of 667 ohm-m, which is interpreted as dry, clay-poor volcanic formations located above sea level in the section. The lower layer in the cross-section shows intermediate resistivity (25 ohm-m), occurring at a depth of 344 feet above sea level (ASL) to a maximum exploration depth of approximately 1,000 feet below sea level (BSL). This lower layer resistivity is interpreted to be likely caused by: 1) Data being distorted by subsurface geologic structures (i.e. 2-D intrusive, dikes, etc.), and/or 2) the presence of significant amounts of fine-grained materials (clay layers) at depth in this area of the site.

Water well information indicates that State Wells 3056-01 (2 feet) and 3156-01 (2 feet) are both reported to contain basal (brackish) groundwater with static water levels (head) as shown on the cross-section. State Well 3155-03 (51 feet) is located near the northeastern portion of the property at elevation 1154 feet and is reported to contain high-level groundwater (per com T. Nance). The difference in head shown at these well locations is likely due to poorly permeable lava flows which are interbedded with more permeable flows or other geologic features at depth in this region of the site. It is also possible that subsurface geologic features are causing non-layered earth conditions (i.e. 2-D dikes, intrusives, clay layers, etc.) that act as possible groundwater damming structures beneath this area of the site.

5.3 HYDROGEOLOGIC INTERPRETATION

The TDEM data is further summarized on the interpretation map shown in Figure 5-2. On the figure Sounding Hoku-1 is colored green and is interpreted to be located within an area that has detected intermediate resistivity at depth in which 2-D structures (i.e. dikes, ash flows, etc.) have likely distorted the true resistivity value. With the present sounding data, the location of the lower groundwater barrier (boundary between basal and possible change to high-level water) is interpreted to be located midway between Well 1 and the center of Sounding Hoku-1. Therefore, the sounding is interpreted to be located within a possible groundwater damming structure, which may consist of fairly abrupt subsurface features such as dikes or possibly from low permeability layers within the lava flows. The potential for high-level groundwater may exist beneath Sounding 1; however, it cannot be confirmed with the present TDEM sounding data.



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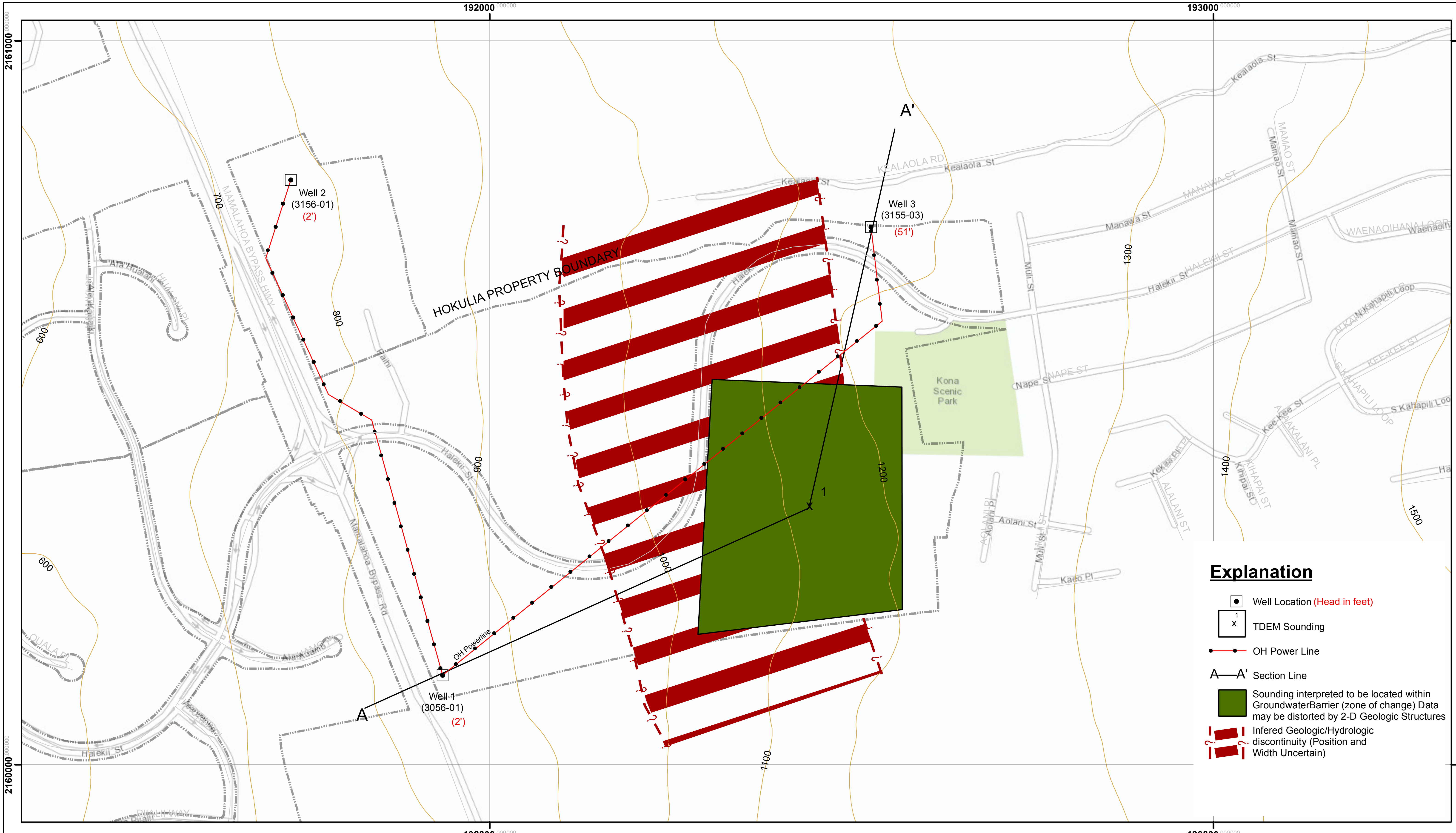
R50129	October, 2014	JMN	RJB	As Shown	5-1



0 200 400 800 1,200 Feet

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Geophysical TDEM Survey
Summary Interpretation Map
South Kona District
Island of Hawaii

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R50129	October, 2014	JMN	RJB	1:4800	5-2

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM survey was to determine whether basal or high-level groundwater underlies a proposed well site on Hokulia property located below the town of Kealakekua, Hawaii. The optimum location for high-level groundwater is expected to occur above groundwater damming structures (i.e. dikes, intrusives, etc.) detected at relatively low surface elevations.

The results from the TDEM survey are shown on Figures 5-1 and 5-2. Sounding Hoku-1 was acquired on the project site between State Wells 3056-01 (2 feet head) and 3155-03 (51 feet head) which are located along Mamalahoa Bypass Road and Halekii Street. The sounding shows intermediate resistivity (25 ohm-m) layers occurring at depth and, due to possible subsurface groundwater damming structures, groundwater is expected to be limited beneath the sounding. In addition, from the data a geologic/hydrologic discontinuity (i.e. altered volcanics, etc.) is interpreted between Well 1 and the center of the sounding, which is possibly causing damming of groundwater in this area. The potential for high-level groundwater is interpreted to exist above Sounding Hoku-1 at higher surface elevation as indicated in Well 3.

Because of limited TDEM data at the project site, additional TDEM soundings located both south and at higher elevation above the Hokulia property will help to define the extent of high-level groundwater resources in this area of the island.

7.0 CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by Zapata Incorporated Senior Geophysicists.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. All original field data files, field notes and observations, and other pertinent information are maintained in the project files and are available for the client to review.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

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APPENDIX A

TECHNICAL NOTE

Zapata Incorporated Project Number R50129

Prepared for:
1250 OCEANSIDE LLC

And:
TOM NANCE WATER RESOURCE ENGINEERING

Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

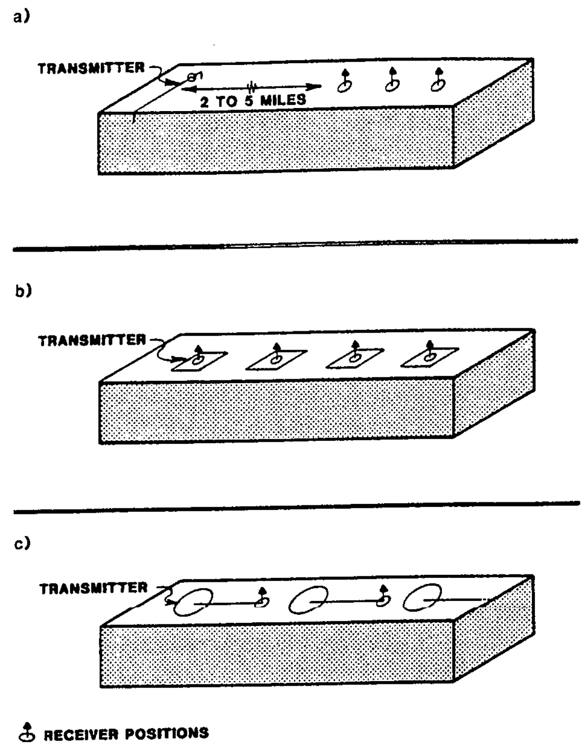

FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

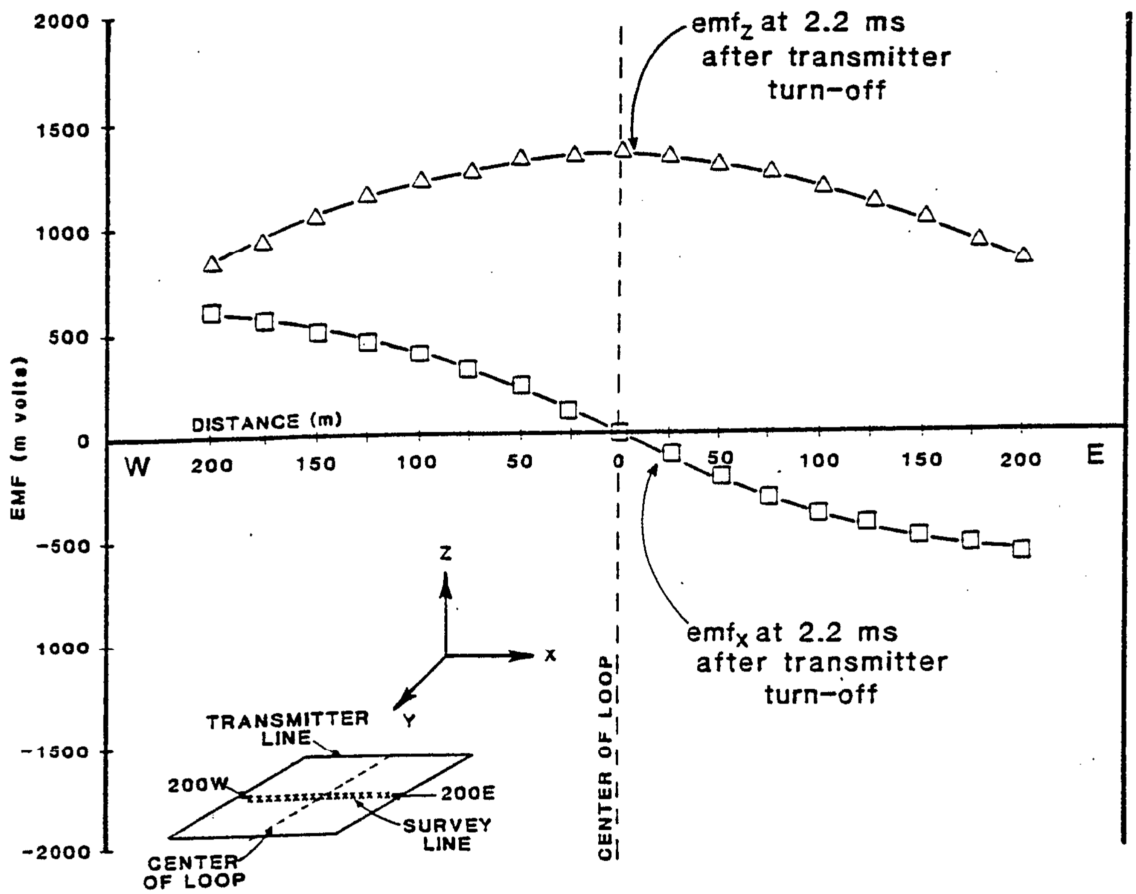

FIG. 2. Measured behavior of the electromotive forces due to vertical (emf_z) and horizontal (emf_x) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf_z measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf_z at late time, is given by

$$emf_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \qquad (1)$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \qquad (2)$$

where

$$\tau \text{ is } \sqrt{\frac{8\,\pi^2 t}{\mu_0\,\sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf_z is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf_z) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

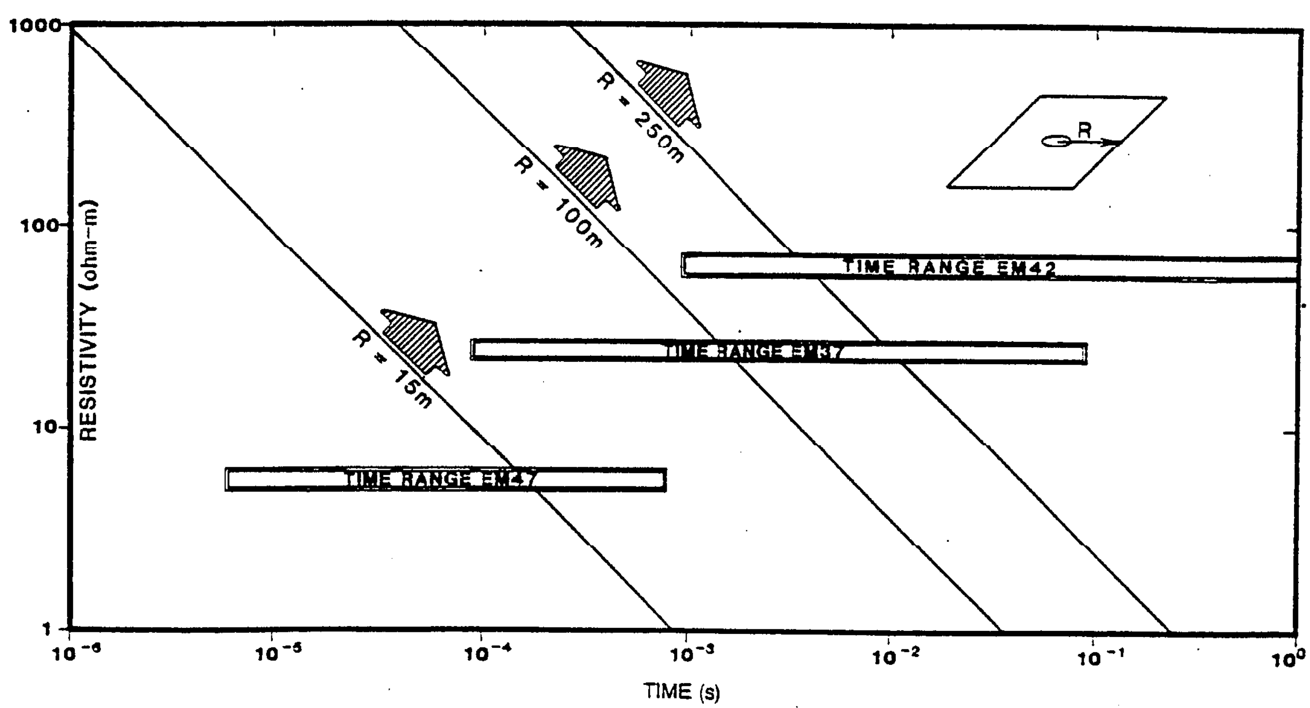

FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

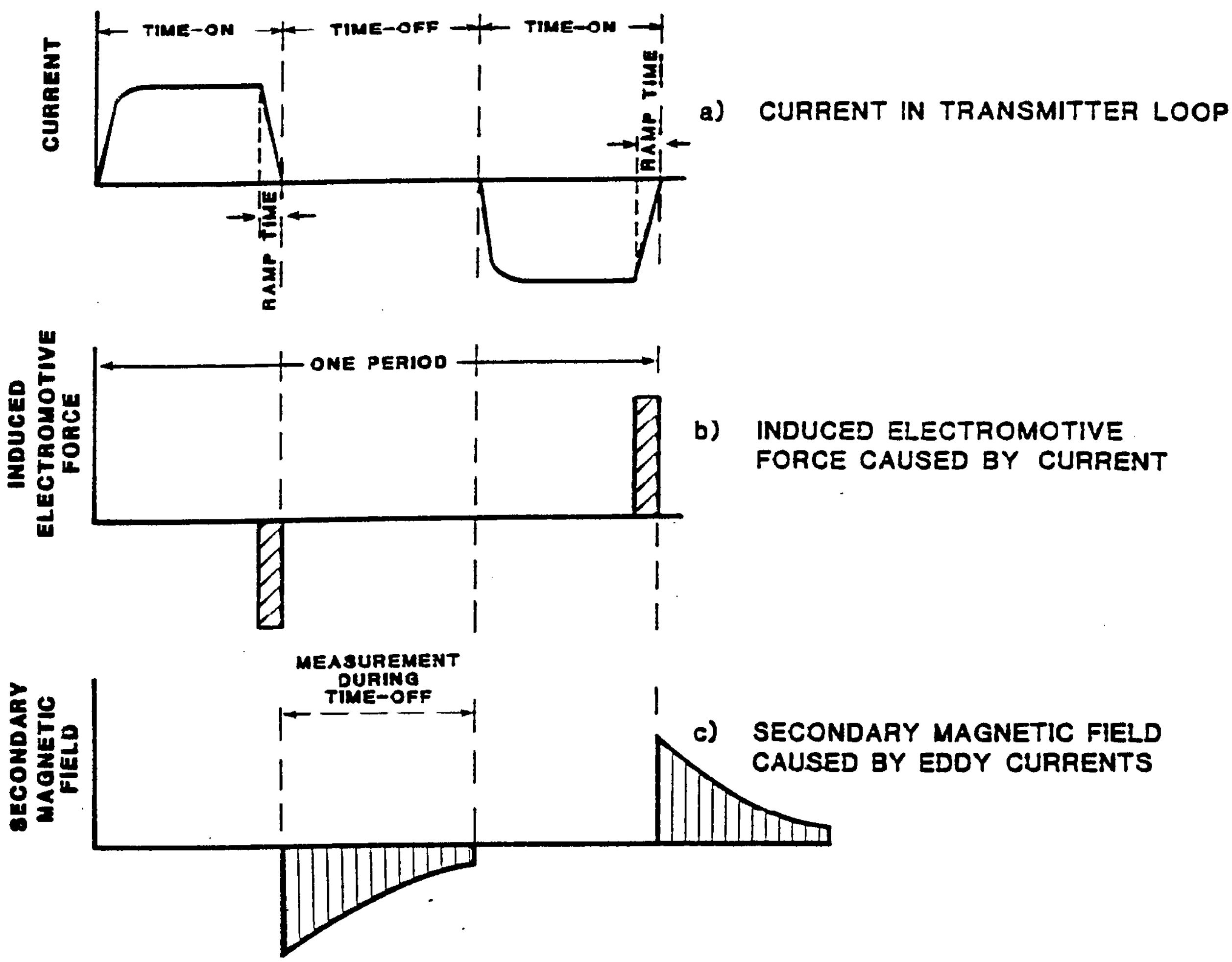

FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

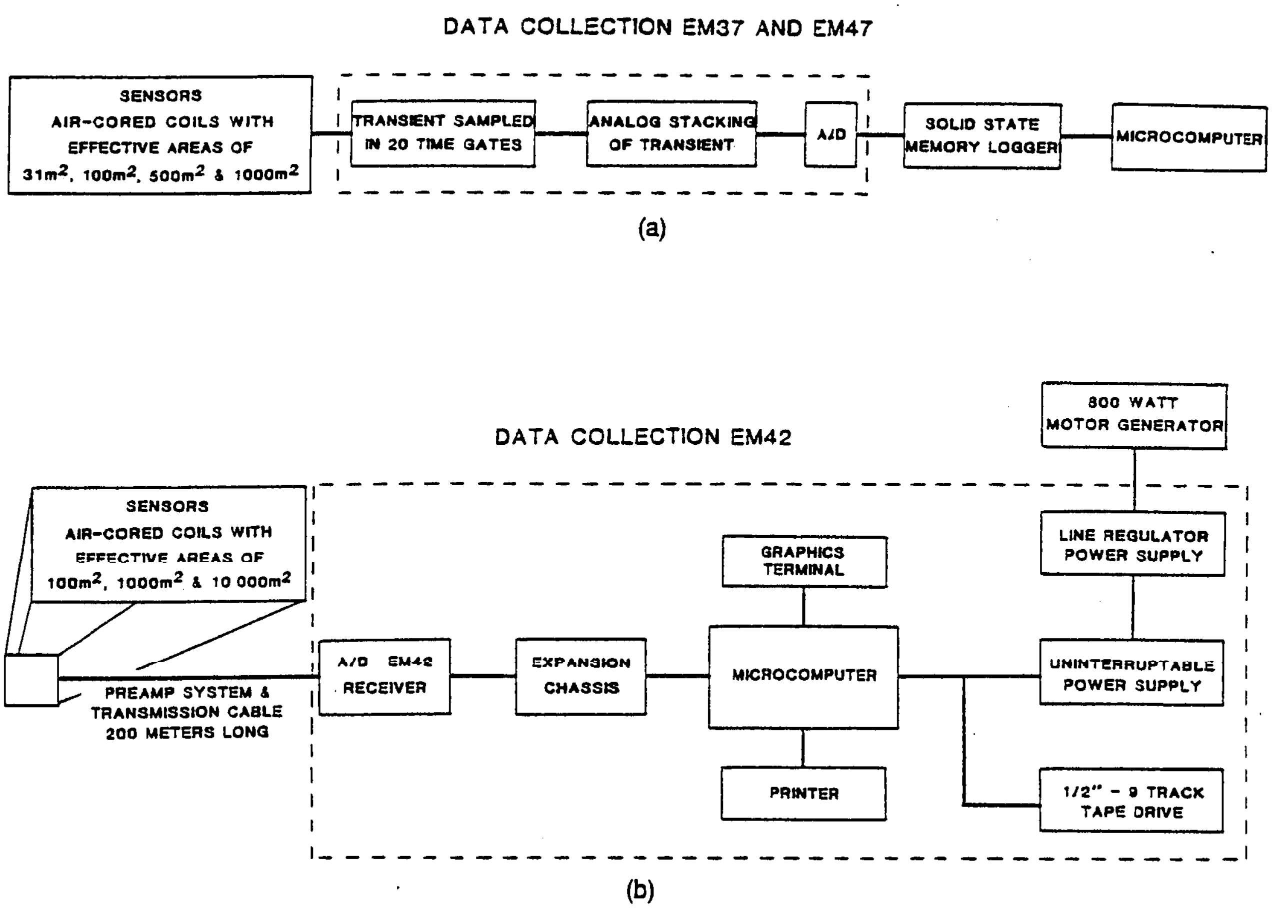

FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf$_z$ decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

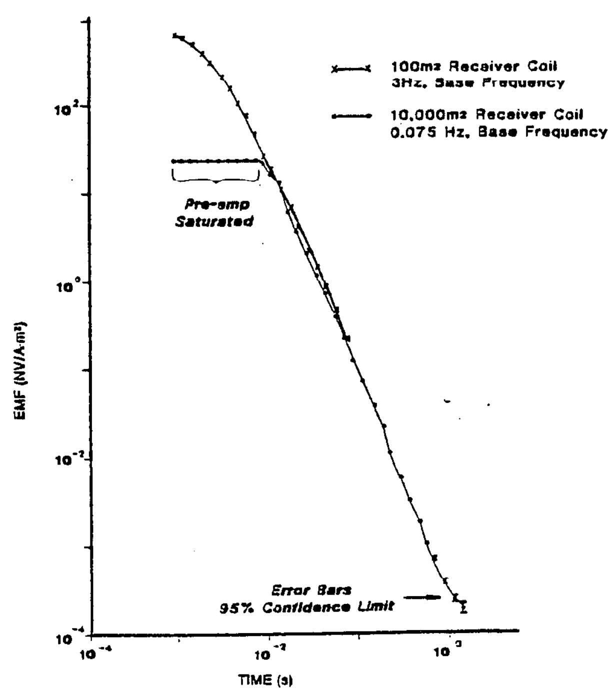

FIG. 6. Emf$_z$ measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

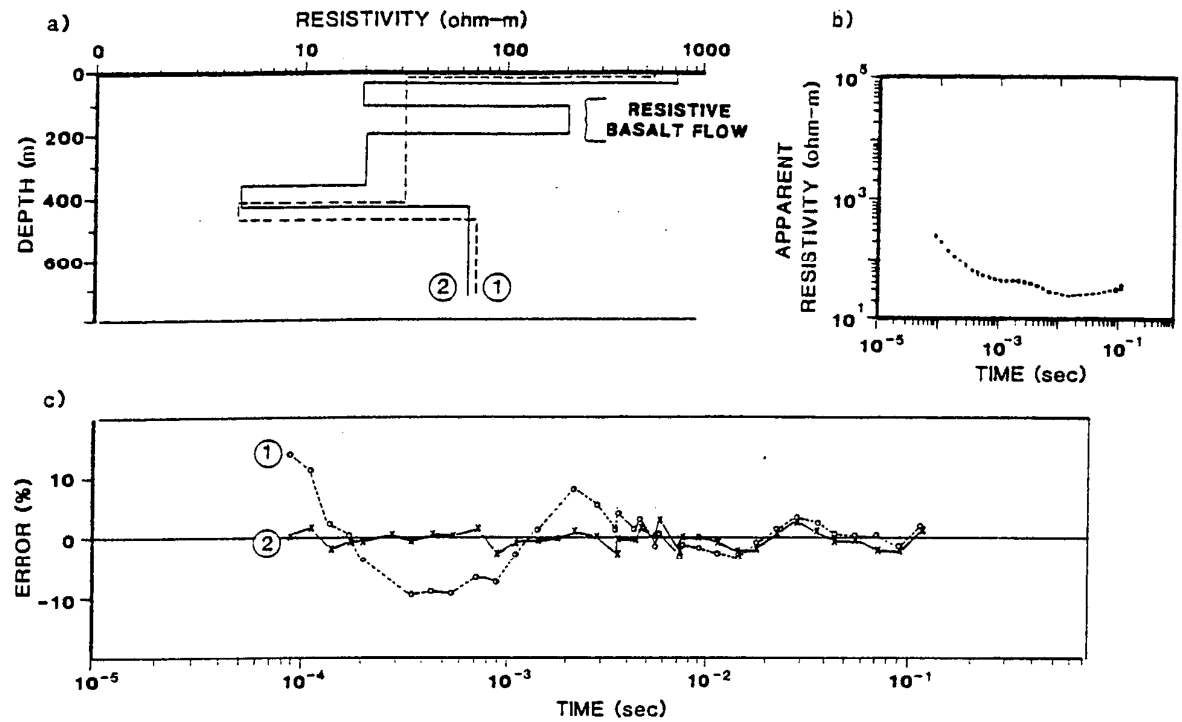

FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

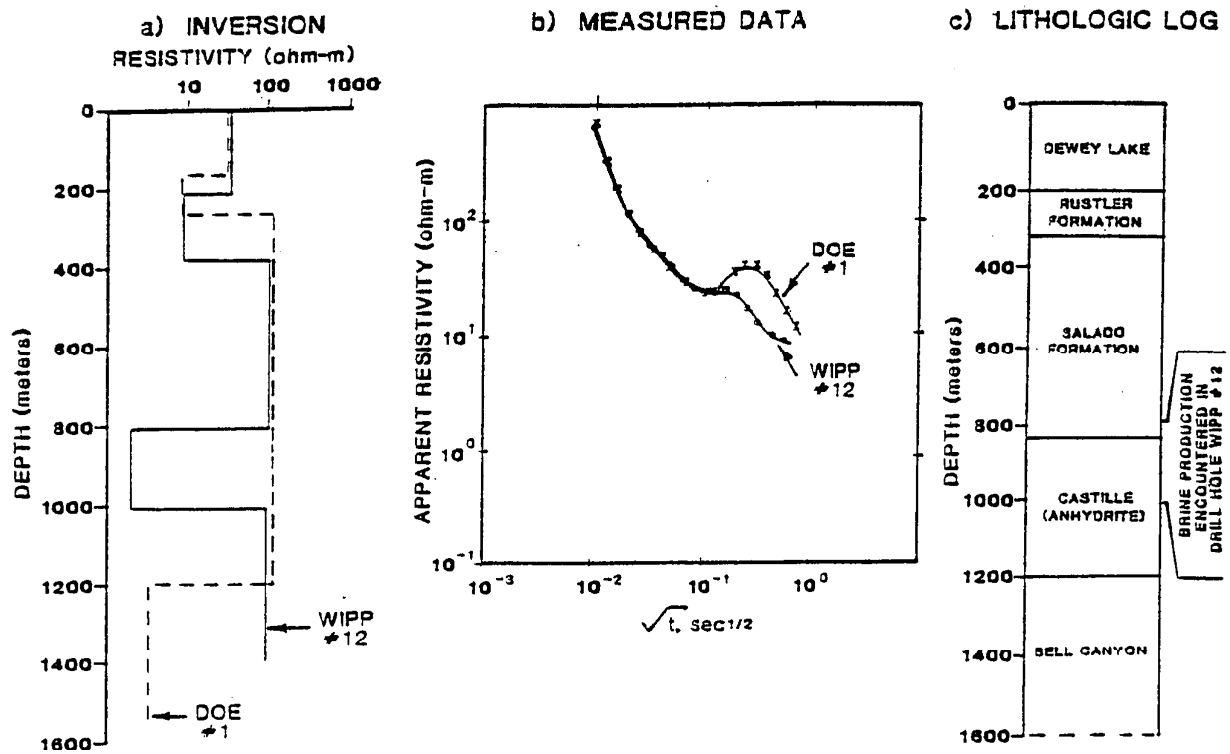

FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

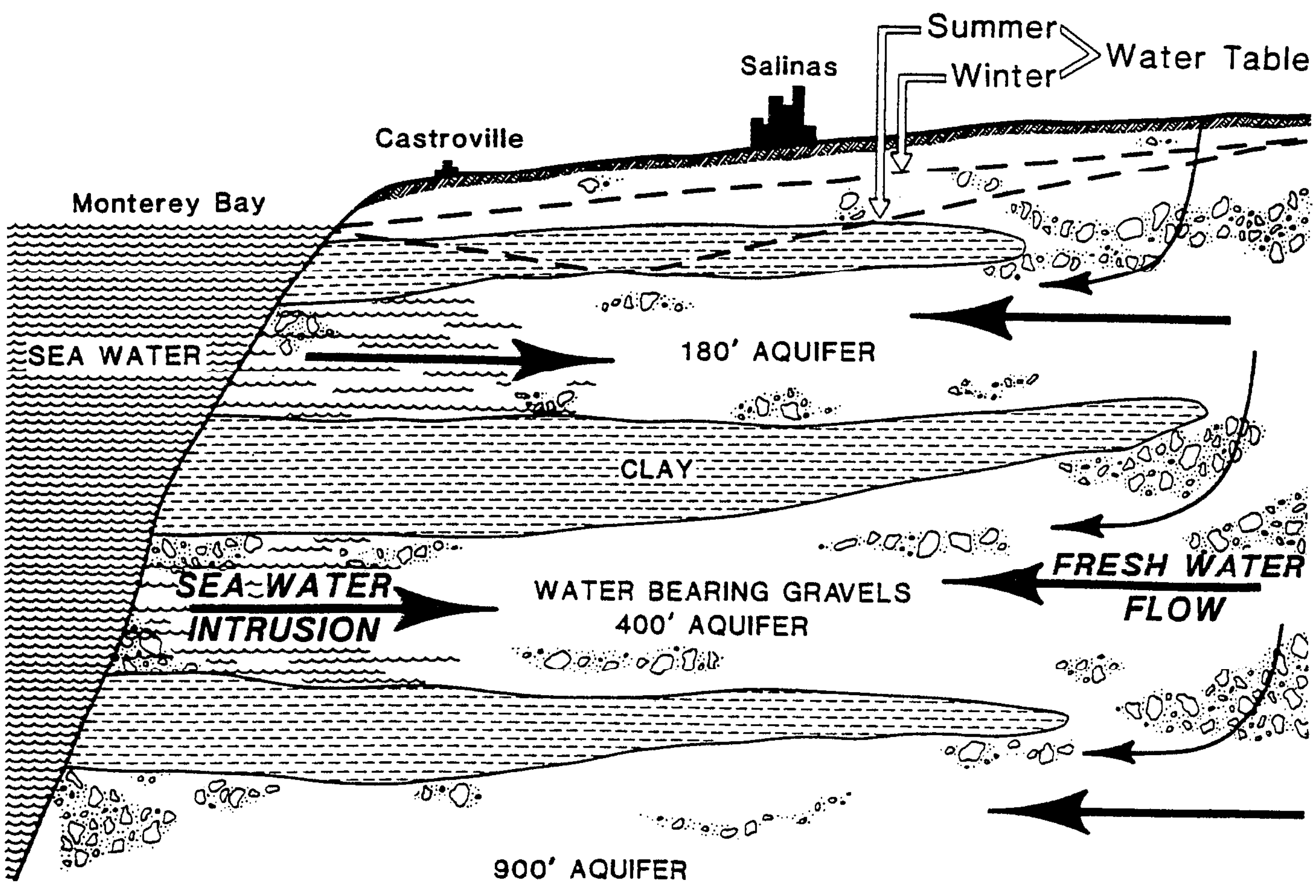

FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 Ω · m (station L24/3) to 18 Ω · m (station L10/1). In the 400-ft aquifer the resistivity increased from 6.0 Ω · m to in excess of 20 Ω · m.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 Ω · m corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 Ω · m formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

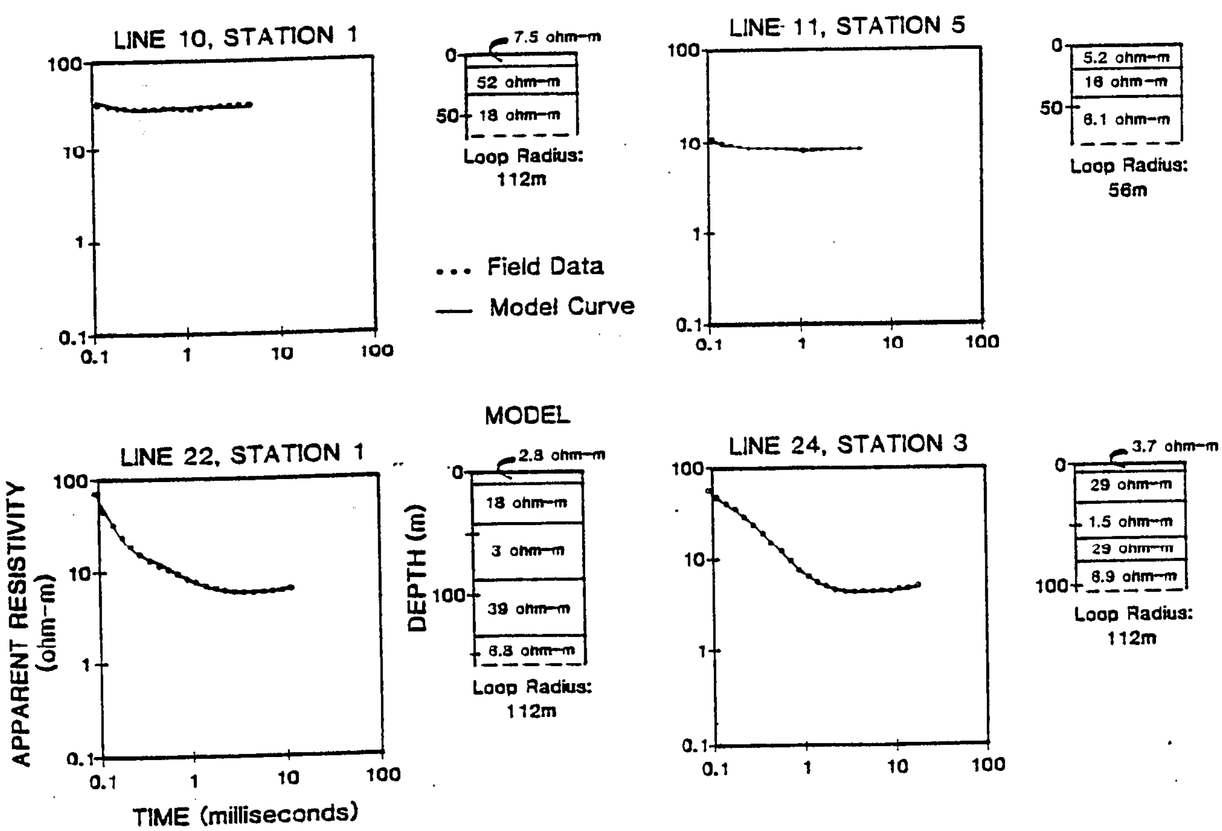

FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

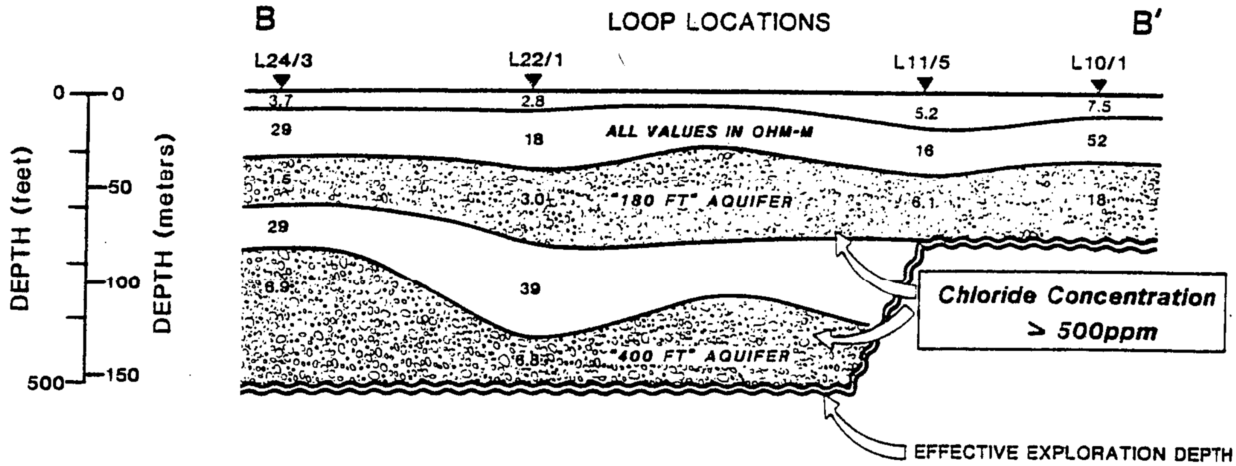

FIG. 11. Geoelectric section B-B' derived from TDEM soundings.

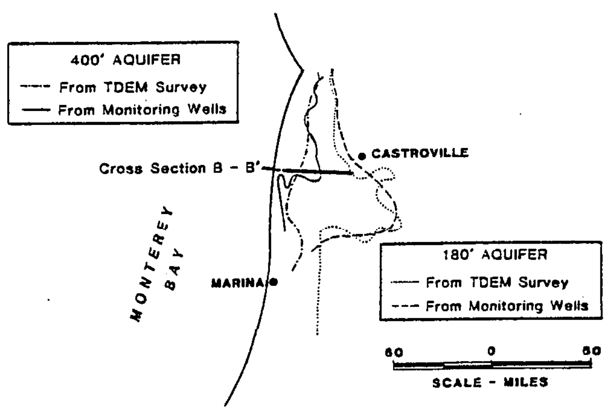

FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.
(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

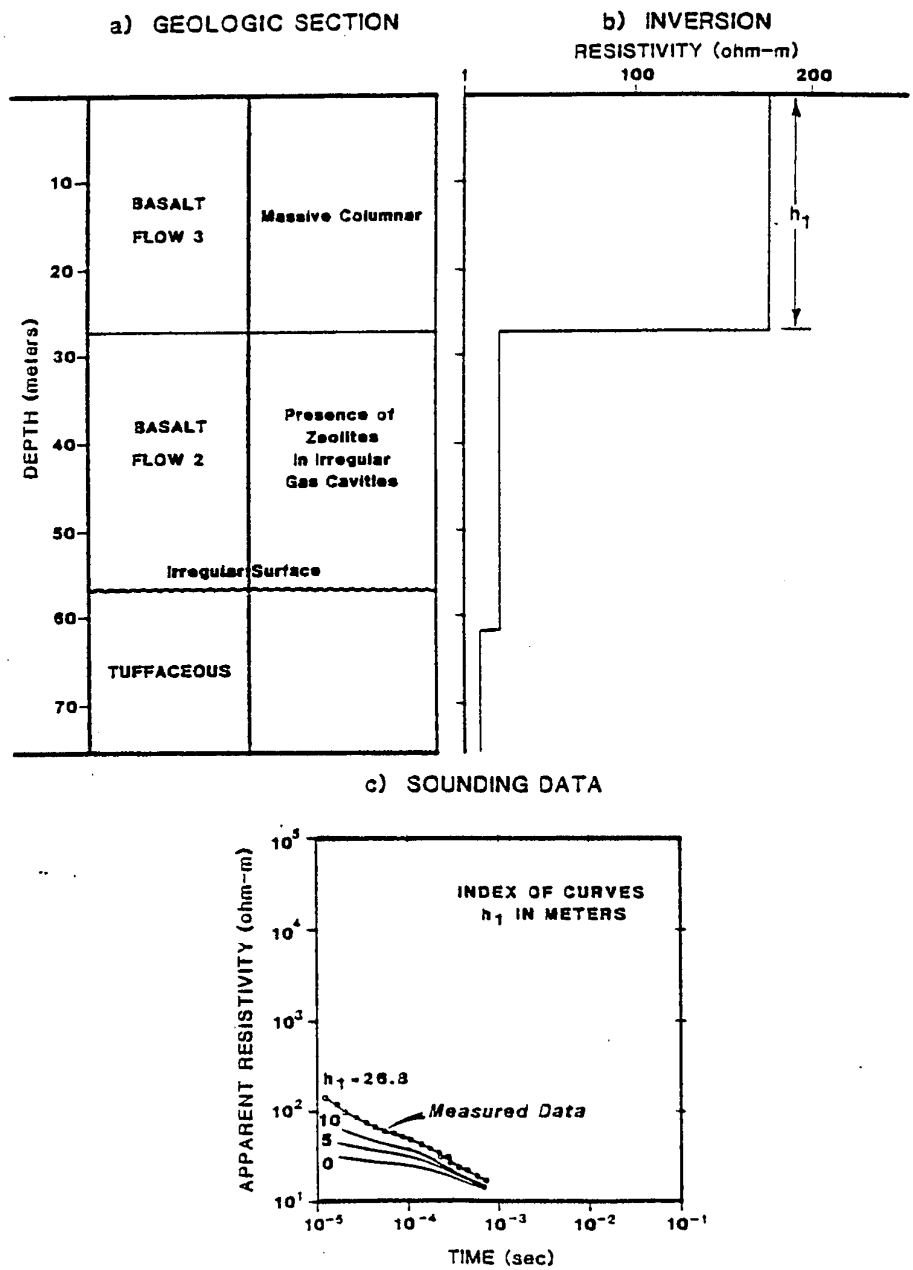

FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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APPENDIX B

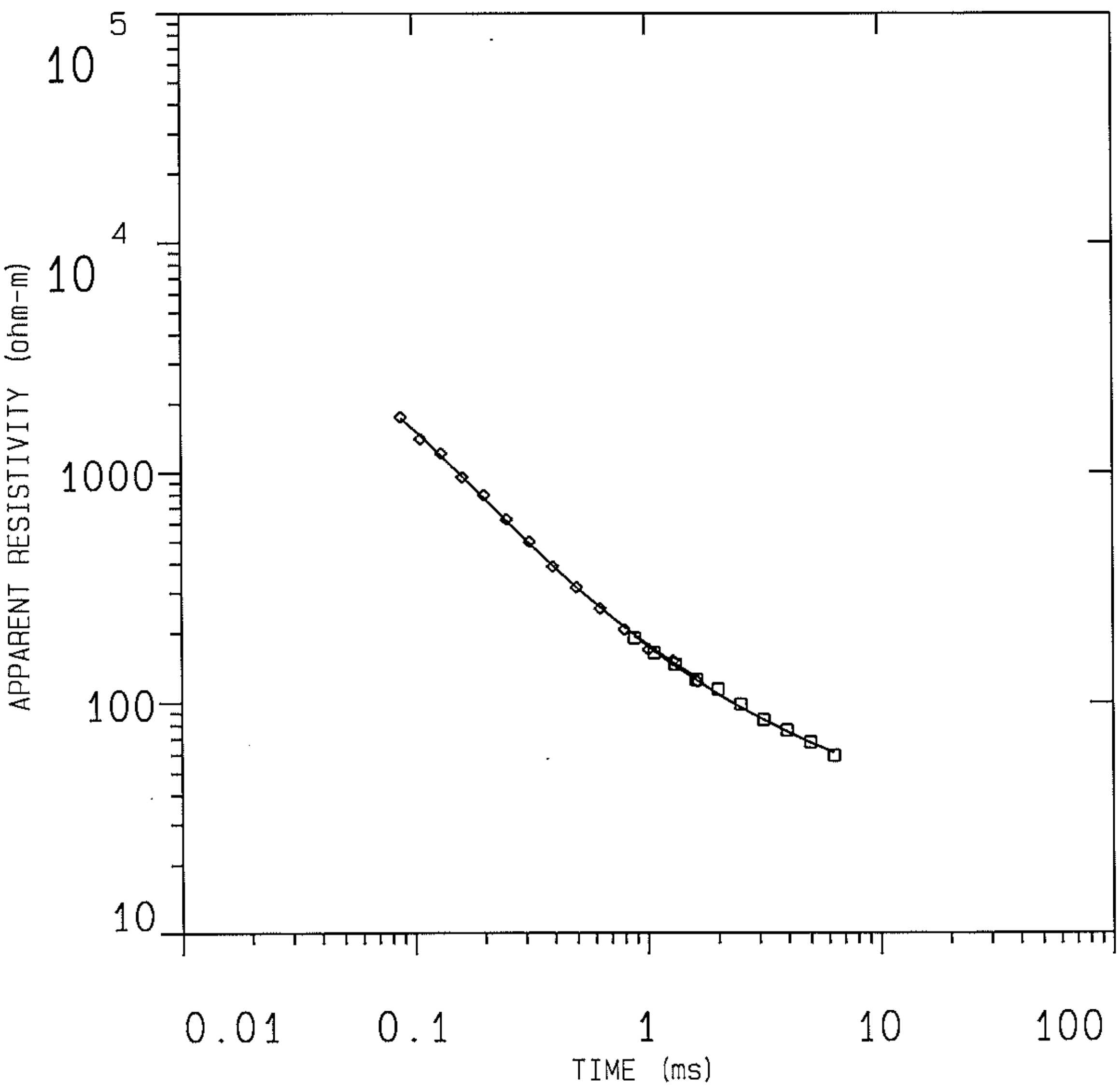
GPS COORDINATES OF TDEM SOUNDING, DATA CURVES AND PRINTOUTS

Zapata Incorporated Project Number R50129

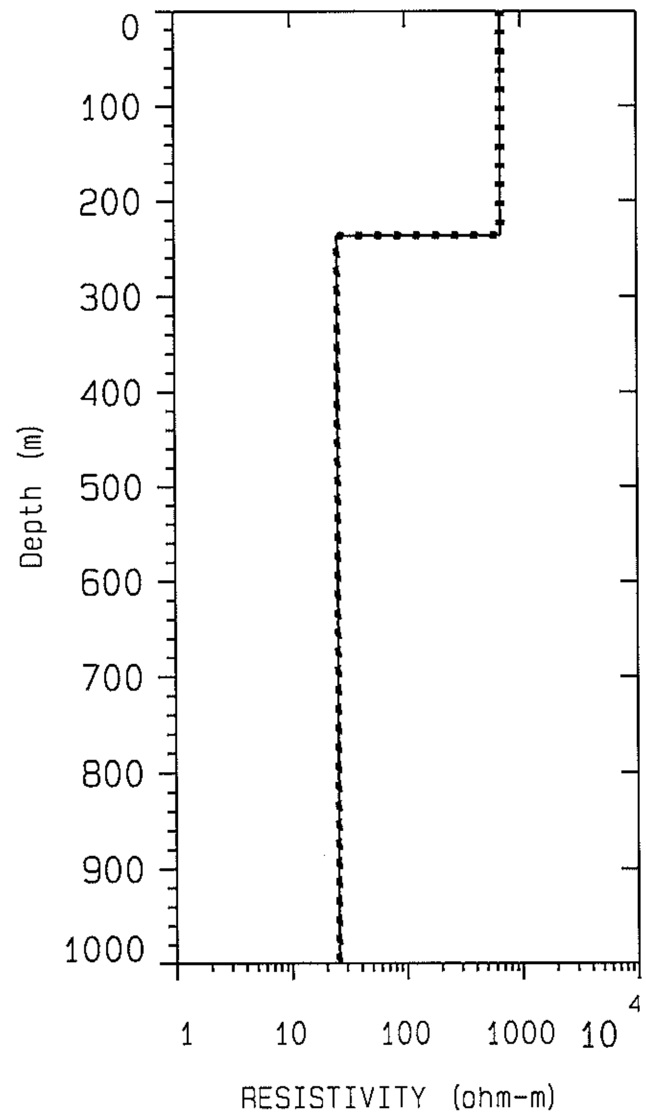
Prepared for:
1250 OCEANSIDE LLC

And:
TOM NANCE WATER RESOURCE ENGINEERING

HOKU-1



10^5
10^4
1000
100
10
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)



0
100
200
300
400
500
600
700
800
900
1000
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: HOKU-1

CLIENT: 1250 Oceanside LLC
LOCATION: Kealakeakua, Hawaii
COUNTY: HAWAII
PROJECT: Hokulia, Hawaii
DATE: 10-14-2014
SOUNDING: 1
ELEVATION: 341.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 305.000 m by 305.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 1.0000 N: 200.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.599 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			341.0	1120.0	
1	667.0	236.1	104.8	343.8	0.354
2	25.43				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	628.475	667.034	714.763
	2	24.434	25.438	26.503
THICK	1	233.147	236.143	239.265
DEPTH	1	233.147	236.143	239.265

CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 5 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.881	342.4	333.0	2.75
2	1.06	264.0	257.0	2.67
3	1.31	187.0	192.5	-2.93
4	1.61	140.3	141.3	-0.691

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
5	2.00	94.59	101.6	-7.45
6	2.50	67.57	71.02	-5.09
7	3.14	48.42	48.55	-0.268
8	3.95	31.87	32.50	-1.95
9	4.99	21.17	21.31	-0.654
10	6.31	14.29	13.72	3.97

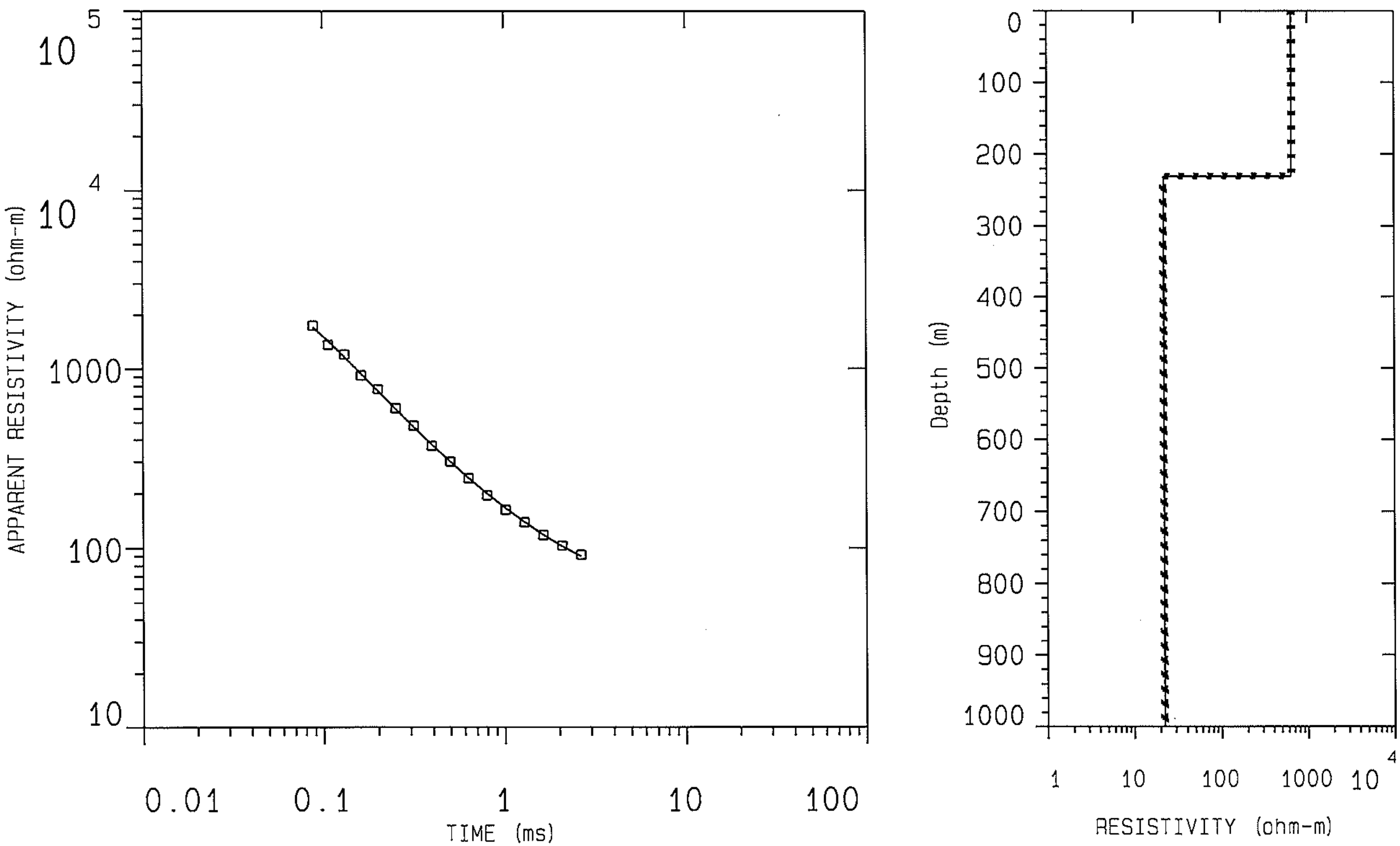
CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 2 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
11	0.0881	3869.6	3918.7	-1.26
12	0.106	3320.1	3145.6	5.25
13	0.131	2460.7	2543.9	-3.38
14	0.161	2102.0	2076.6	1.20
15	0.200	1619.6	1693.7	-4.57
16	0.250	1337.6	1367.3	-2.21
17	0.314	1056.9	1088.8	-3.02
18	0.395	867.1	855.4	1.34
19	0.499	659.7	659.0	0.112
20	0.631	506.0	498.9	1.40
21	0.799	384.1	370.4	3.55
22	1.01	287.2	268.7	6.42
23	1.28	186.8	191.2	-2.36
24	1.63	140.7	132.6	5.77

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.89		
P 2	-0.03	0.96	
T 1	0.02	0.01	1.00

HOKU-1N


APPARENT RESISTIVITY (ohm-m)
10^5
10^4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: HOKU-1N

CLIENT:	1250 Oceanside LLC	DATE:	10-15-2014
LOCATION:	Coil located 100 ft North	SOUNDING:	1
COUNTY:	HAWAII	ELEVATION:	341.00 m
PROJECT:	Hokulia, Hawaii	EQUIPMENT:	Geonics PROTEM
LOOP SIZE:	305.000 m by 305.000 m	AZIMUTH:	
COIL LOC:	0.000 m (X), 0.000 m (Y)	TIME CONSTANT:	NONE
SOUNDING COORDINATES:	E: 100.0000 N: 1.0000	SLOPE:	NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.212 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			341.0	1120.0	
1	651.9	230.4	110.5	362.5	0.353
2	22.06				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	606.606	651.984	718.423
	2	20.358	22.066	23.823
THICK	1	226.855	230.463	233.696
DEPTH	1	226.855	230.463	233.696

CURRENT:	14.00 AMPS	EM-58	COIL AREA:	100.00 sq m.
FREQUENCY:	30.00 Hz	GAIN: 2	RAMP TIME:	150.00 muSEC

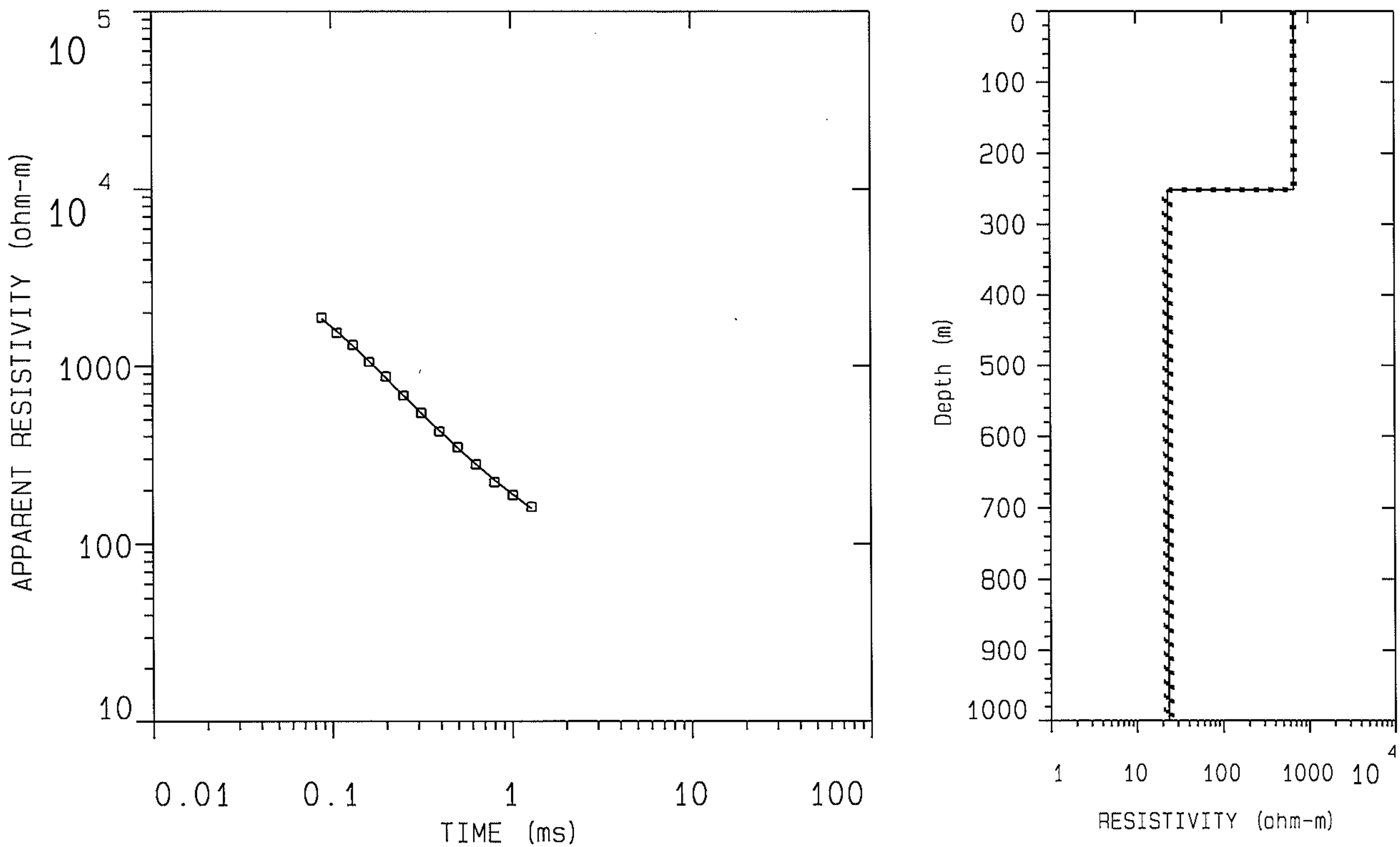
No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	3886.8	4002.4	-2.97
2	0.106	3488.5	3233.5	7.30
3	0.131	2511.0	2632.9	-4.85
4	0.161	2227.1	2163.2	2.87

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
5	0.200	1706.6	1775.6	-4.04
6	0.250	1417.3	1442.4	-1.77
7	0.314	1123.7	1156.1	-2.88
8	0.395	933.6	914.2	2.07
9	0.499	709.2	708.9	0.0300
10	0.631	543.6	540.6	0.550
11	0.799	416.8	404.2	3.02
12	1.01	304.9	295.5	3.07
13	1.28	213.4	211.7	0.766
14	1.63	148.6	148.0	0.430
15	2.08	99.93	101.0	-1.15
16	2.64	65.22	67.30	-3.19

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.89		
P 2	-0.06	0.91	
T 1	0.02	0.01	1.00
	P 1	P 2	T 1

HOKU-1S



APPARENT RESISTIVITY (ohm-m)
10^5
10^4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: HOKU-1S

CLIENT:	1250 Oceanside LLC	DATE:	10-15-2014
LOCATION:	Coil located 100 ft South	SOUNDING:	1S
COUNTY:	HAWAII	ELEVATION:	341.00 m
PROJECT:	Hokulia, Hawaii	EQUIPMENT:	Geonics PROTEM
LOOP SIZE:	305.000 m by 305.000 m	AZIMUTH:	
COIL LOC:	0.000 m (X), 0.000 m (Y)	TIME CONSTANT:	NONE
SOUNDING COORDINATES:	E: 100.0000 N: -1.0000	SLOPE:	NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 2.137 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			341.0	1120.0	
1	675.1	251.3	89.64	293.9	0.372
2	23.38				

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	639.681	675.110	720.619
	2	20.907	23.390	26.004
THICK	1	248.559	251.353	253.969
DEPTH	1	248.559	251.353	253.969

CURRENT:	14.00 AMPS	EM-58	COIL AREA:	100.00 sq m.
FREQUENCY:	30.00 Hz	GAIN: 2	RAMP TIME:	150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	3484.1	3547.4	-1.81
2	0.106	2880.2	2781.2	3.43
3	0.131	2183.2	2207.7	-1.12
4	0.161	1807.5	1785.6	1.21

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
5	0.200	1411.7	1450.7	-2.76
6	0.250	1169.6	1172.8	-0.278
7	0.314	929.9	938.3	-0.908
8	0.395	751.4	741.5	1.31
9	0.499	569.8	576.8	-1.23
10	0.631	441.8	440.4	0.323
11	0.799	344.4	330.6	4.01
12	1.01	244.9	242.7	0.905
13	1.28	169.0	174.6	-3.30

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.94		
P 2	-0.08	0.79	
T 1	0.01	0.01	1.00
	P 1	P 2	T 1

APPENDIX C

CD WITH FILES OF REPORT AND FIGURES

Zapata Incorporated Project Number R50129

Prepared for:
1250 OCEANSIDE LLC

And:
TOM NANCE WATER RESOURCE ENGINEERING